A Precautionary Approach to Fishery Control Rules Based on Surplus Production Modeling

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Abstract.- A risk-averse control rule, derived from surplus production model parameters and associated uncertainty, was developed to manage fisheries for maximum sustainable yield (MSY) and rapid rebuilding of overfished stocks. The proposed control rule consists of an overfishing threshold of F_{MSY} (the fishing mortality which produces MSY on a continuing basis, equal to half the intrinsic population growth rate, *r*) when biomass is greater than B_{MSY} (the biomass which can produce MSY). When biomass is less than B_{MSY}, the threshold F is derived as the maximum F which allows rebuilding to B_{MSY} in a specified period. Assuming logistic population growth, threshold F is a function of biomass relative to B_{MSY} and *r*. Precautionary levels of target F are derived from uncertainty in the estimate of *r*. Target F for a healthy stock is less than F_{MSY}, because it is derived from a lower quantile of the conditional probability distribution of *r* (designated as r'). At low stock size, target F is the maximum F which allows rebuilding to B_{MSY} in the specified period, assuming that r' is the intrinsic growth rate. The proposed control rule was applied to results of a nonequilibrium production model (ASPIC) of the Georges Bank yellowtail flounder stock, which is currently rebuilding from a collapsed state. Four years appears to be an appropriate rebuilding period for this stock, because *r* was estimated to be relatively rapid (0.60). Target F is derived from the 10th bootstrap percentile of *r* (r'=0.53; $F_{MSY}'=r'/2$=0.26). Conditional stochastic projection of ASPIC results suggests that, after four years of a rebuilding target determined by the control rule, there is high probability that the stock will grow to exceed B_{MSY}, and then produce 95% of MSY at the long-term target F. However, the cumulative risk of not achieving B_{MSY} in the specified period substantially increases if the rebuilding period is increased. The proposed control rule may be applied to other stocks which can be reliably modeled by logistic growth. Target F will be slightly less than the overfishing limit if *r* is well estimated, and substantially less than the limit if *r* is poorly estimated. However, the appropriate rebuilding time may be longer for slower-growing stocks (*r*<0.6) and shorter for faster-growing stocks (*r*>0.6) to conserve similar levels of relative biomass.

Introduction

The Sustainable Fisheries Act emphasizes the need to conserve U.S. fishery resources for long-term maximum sustainable yield (MSY) through precautionary management. Proposed guidelines on managing sustainable fisheries include several components: 1) preventing overfishing while producing MSY on a continuing basis; 2) defining overfishing as a rate of fishing mortality (F) that exceeds the threshold rate associated with producing MSY (F_{MSY}); 3) defining an overfished state as a stock size that is less than a minimum stock size threshold, which is the stock biomass that will allow rebuilding to the MSY stock biomass (B_{MSY}) in ten years; and 4) adopting fishery control rules that incorporate uncertainty of MSY reference point estimates, so that fishing targets are risk averse (DOC 1997). The proposed guidelines recommend that management be based on a ‘precautionary approach’ which has been endorsed by several international fishery management agencies (FAO 1995, UN 1995, ICES 1997, Serchuk et al. 1997). Although agencies have different specific guidelines for implementing a precautionary approach, a common feature is that target fishing levels should have low risk of exceeding MSY reference points. This study was conducted to derive a fishery control rule that conforms to the proposed national guidelines on sustainable fisheries. The control rule was designed to provide guidance on appropriate target and threshold levels of F conditioned on levels of stock biomass with the objectives of quickly rebuilding depleted stocks to levels that can produce MSY.

Surplus production models can provide guidance on stock status, MSY reference points, and associated uncertainties. Results from a nonequilibrium production model (ASPIC, Prager 1994, 1995) played a central role in the most recent stock assessment of Georges Bank yellowtail flounder (Cadrin et al. 1997, Neilson et al. 1997). Estimates of biomass and F from ASPIC agreed closely with estimates from an age-structured model and were considered reliable for management advice (DFO 1997, NEFSC 1997, NRC 1998). Stock assessment results show that F exceeded the level of maximum yield-per-recruit (F_{max}) from the late 1950s to the early 1990s. During this period, the fishery was managed using several strategies (e.g., national quotas, minimum size limits, minimum mesh sizes, spawning area closures, and trip limits). By 1994, the stock was considered to have collapsed (NEFSC 1994). Subsequently, amendments to the Northeast Multispecies Fishery Management Plan were designed to rebuild yellowtail flounder and other principal groundfish stocks to threshold levels of spawning stock biomass (SSB; for

Georges Bank yellowtail flounder, the threshold was 10,000 mt) by limiting days at sea, closing large areas year-round, increasing minimum mesh size, and imposing trip limits for some sectors of the fishery. In 1995, Canada also began to imposed restrictive catch quotas. The most recent assessment of the Georges Bank yellowtail flounder stock indicated that biomass had increased to above the rebuilding threshold, but was well below B_{MSY} (Cadrin et al. 1997, Neilson et al. 1997). Precautionary management measures are needed to allow continued rebuilding of the Georges Bank yellowtail flounder stock.

Surplus Production Modeling

A nonequilibrium surplus production model incorporating covariates (ASPIC; Prager 1994, 1995) was applied to total catch and survey biomass indices for the Georges Bank yellowtail flounder stock. A previous application of ASPIC to the Georges Bank yellowtail flounder stock (Cadrin et al. 1997, Neilson et al. 1997) was revised by including discard estimates from U.S. fisheries (1963-1972 from M. Parrack, unpublished[1]; 1973-1990 from Conser et al. 1991, 1991-1993 from NEFSC 1994, 1994-1996 from Cadrin et al. 1997). Total catch averaged more than 18,000 mt during 1963-1976, decreased to approximately 7,000 mt from 1978-1981, increased temporarily to more than 11,000 mt in 1982 and 1983, but declined to less than 7,000 mt after 1984. Biomass indices from NEFSC groundfish surveys generally declined at a rate of 10% per year since 1963, with a temporary increase in the early 1980s (Figure 1). Declines in average weight per tow suggest that current biomass levels are about 10% of levels observed in the 1960s. However, there are indications of increasing stock biomass levels in the last two years. The weight per tow index from the Canadian survey increased to a peak in 1996. Correlations among survey biomass indices were moderate to strong (r= 0.5, 0.7, and 0.8).

The production model assumes logistic population growth, in which the change in stock biomass over time (dB_t/dt) is a quadratic function of biomass (B):

$$dB_t/dt = rB_t - (r/K)B_t^2 \qquad (1)$$

where r is the intrinsic rate of population growth, and K is carrying capacity. For a fished stock, the rate of change is also a function of catch (C):

$$dB_t/dt = rB_t - (r/K)B_t^2 - C_t \qquad (2)$$

Biological reference points can be calculated from the production model parameters:

$$MSY = K\, r / 4 \qquad (3)$$
$$B_{MSY} = K / 2 \qquad (4)$$
$$F_{MSY} = r / 2 \qquad (5)$$

Initial biomass (expressed as a ratio to B_{MSY}: *B1R*), *r*, and MSY were estimated using nonlinear least squares of survey residuals. Catch per unit effort (CPUE) from the NEFSC fall survey contributed to the total sum of squares as a series of observed effort (E=1/CPUE/C). The NEFSC spring survey and the Canadian survey contributed as independent biomass indices. Survey residuals were randomly resampled 500 times to approximate precision and model bias.

Most of the variance in survey indices was explained by the model (R^2= 0.78, 0.56, and 0.84). Model results indicate that a maximum sustainable yield of 14,500 mt can be produced when stock biomass is approximately 48,600 mt (B_{MSY}) and F is 0.30 (F_{MSY}). The MSY estimate is slightly lower than a previous MSY estimate (16,000 mt, NEFSC 1995). The B_{MSY} estimate is not directly comparable to published estimates of SSB_{MSY}, because it pertains to total stock biomass rather than mature biomass, but the estimate is between the current

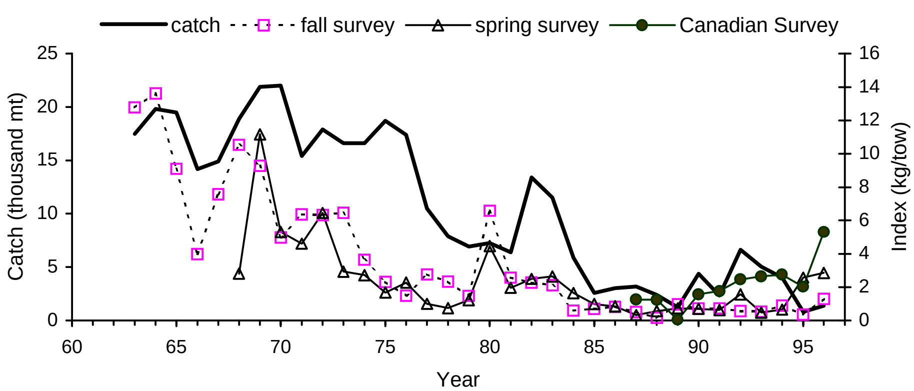

Figure 1. Input data for surplus production analysis of Georges Bank yellowtail flounder.

[1]Parrack, M.L. A catch analysis of the Georges Bank yellowtail flounder stock. Northeast Fisheries Center, Woods Hole, MA.

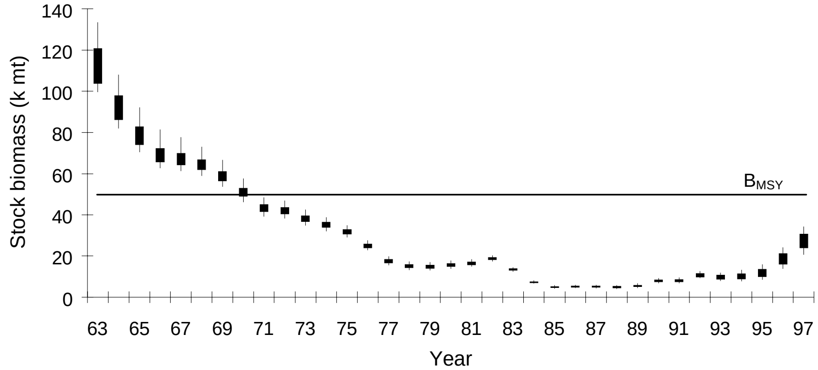

Figure 2. Biomass estimates from surplus production analysis of Georges Bank yellowtail flounder. Box plots indicate 50% and 80% confidence intervals.

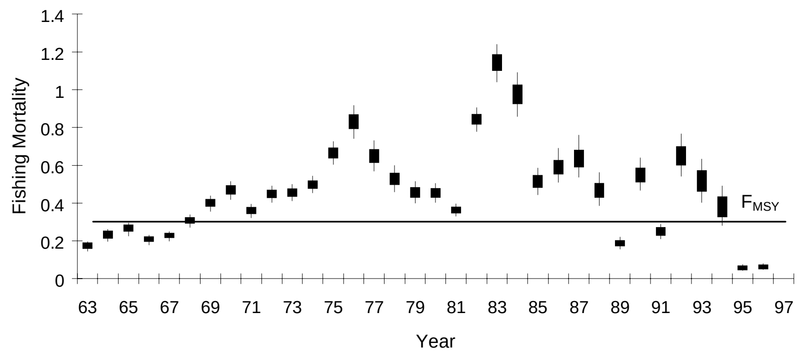

Figure 3. Fishing mortality estimates from surplus production analysis of Georges Bank yellowtail flounder. Box plots indicate 50% and 80% confidence intervals.

rebuilding target (10,000 mt SSB) and a previous estimate of SSB_{MSY} (65,000 mt, NEFSC 1995). The MSY reference points from ASPIC are similar to those estimated from stock-recruit data (Overholtz 1999).

Estimated stock biomass was greater than 50,000 mt in the 1960s (Figure 2). However, after 1967, F exceeded F_{MSY}, and biomass declined further. F continued to exceed F_{MSY} until 1995 (Figure 3). Biomass was reduced to less than B_{MSY} beginning in 1971, and continued declining to approximately 5,000 mt in the 1980s. In 1995, F sharply decreased, and biomass increased to 40% of B_{MSY} in 1996. Estimates of stock biomass and F from the surplus production model were similar to those from virtual population analysis (Cadrin et al. 1997, Neilson et al. 1997). Bootstrap analysis showed that MSY, r, K, B_{MSY}, and F_{MSY} were well estimated (relative interquartile range, IQR<10%), *B1R* and survey catchability coefficients (q) were slightly more variable (IQR=11% to 31%), and ratios of current conditions to MSY conditions were less precise (IQR=28 to 32%).

Exploratory ASPIC analyses were performed which included historical catch and landings-per-unit-effort as an index of biomass from 1943-1966 (Lux 1964, 1969a), but the model did not fit the data well (Cadrin et al. 1997). Estimates of MSY, r, K, and q were not sensitive to extending the time series, including the LPUE series, or removing the penalty function for *B1R*>K (Prager 1994).

Rebuilding Trajectories

The stock's capacity to rebuild from low biomass levels can be assessed by simulating population growth using parameter estimates from the production model. Assuming logistic growth, minimum stock size required to achieve B_{MSY} in ten years depends on the current level of biomass, F, and the stock's intrinsic growth rate (r). There is a threshold stock size, below which B_{MSY} cannot be attained in 10 years, even at F=0. Threshold combinations of maximum F and minimum biomass required to achieve B_{MSY} in ten years can be projected using an annual difference equation:

$$B_{t+1} = B_t + (r - F_t)B_t - (r/K)B_t^2 \qquad (6)$$

Therefore, at any fixed F, a minimum biomass (B_0), which is less than B_{MSY}, can be solved so that $B_{10}=B_{MSY}$. If biomass is expressed as a ratio to B_{MSY} ($B = B/B_{MSY}$), the equation becomes a function of *r*, F, and the current level of relative biomass, because $K=2B_{MSY}$:

$$B'_{t+1} = B'_t + (r-F_t)B'_t - (r/2)B'^2_t \qquad (7)$$

Solving for several values of relative F (F/F_{MSY}) shows that slow growing stocks (e.g., *r*=0.2) cannot grow to B_{MSY} within ten years if the stock is reduced to approximately 25% of B_{MSY} (even with no fishing, Figure 4). Logistic growth with faster growth rates (i.e., greater values of *r*) implies that stocks can be depleted to extremely low levels and still grow to B_{MSY} in ten years. However, stocks at extremely low biomass levels are likely to have unstable age structures that may reduce the stock's general growth capacity. Therefore, managing fast-growing stocks based on ten-year rebuilding horizons would be risky, and it would not be prudent to base minimum stock size thresholds on ten-year rebuilding horizons for fast-growing stocks (DOC 1997).

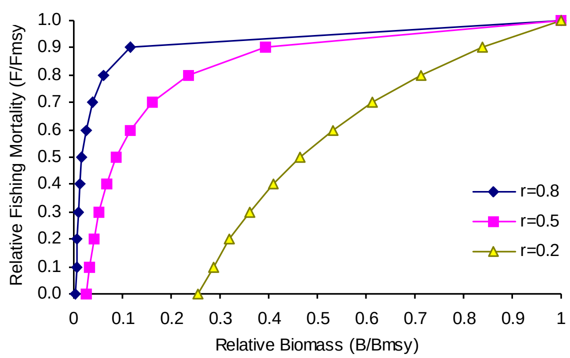

Figure 4. Maximum F and minimum biomass required to achieve B_{MSY} in ten years at several intrinsic rates of increase (*r*).

More appropriate rebuilding horizons for fast-growing stocks can be determined by inspecting rebuilding isopleths (curves of paired maximum F and minimum biomass to achieve B_{MSY}) over one to ten-years. For example, rebuilding isopleths for Georges Bank yellowtail flounder (*r*=0.60) are shown in Figure 5.

Control Rule

Production model results provide several limit reference points for managing sustainable yield. For example, when stock biomass of Georges Bank yellowtail flounder is greater than B_{MSY} (48,600 mt), F should be limited to less than F_{MSY}, which is 0.30. This corresponds to the fixed-F MSY control rule described by Thompson (1999). A precautionary long-term target can be derived from the conditional bootstrap distribution of *r*. For the yellowtail flounder example, the 10^{th} bootstrap percentile of bootstrap *r* estimates (r') was 0.53 and the associated target F would be 0.26 ($F_{MSY}' = r'/2$). A target F of 0.26 should have approximately a 90% chance of being below F_{MSY}.

Rebuilding times and limit F's for low stock sizes of Georges Bank yellowtail flounder can be derived from the rebuilding isopleths in Figure 5. Requiring the stock to rebuild within four years suggests that fishing should stop when the stock is reduced to approximately 11,000 mt (¼B_{MSY}). At the 1996 level of mean biomass (23,000 mt), an F of less than 0.18 should allow the stock biomass to rebuild to B_{MSY} within four years. Target rebuilding F's for low stock sizes can be also derived from r'. For example, a target F of 0.11 would allow rebuilding from current biomass to B_{MSY} in four years if r' is assumed to be the intrinsic growth rate. An example of the proposed control rule is illustrated in Figure 6.

Stochastic projection, incorporating uncertainty in

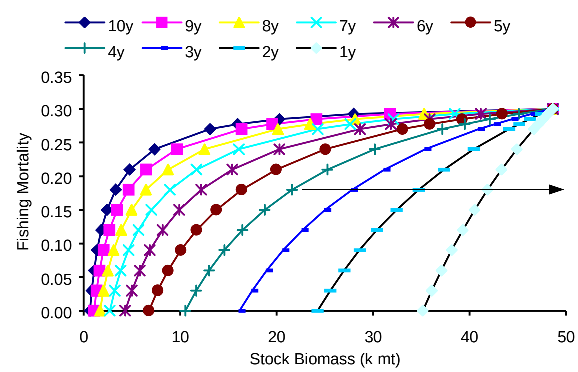

Figure 5. Rebuilding isopleths of maximum F and minimum stock biomass that allow rebuilding to B_{MSY} over several time horizons (1-10 y) for Georges Bank yellowtail flounder. Arrow indicates a 4-year rebuilding scenario from the current biomass level.

current biomass and model parameters for Georges Bank yellowtail flounder, with F= 0.11 for the next four years (1997-2000) suggests that there is approximately a 60% probability that the stock will rebuild to B_{MSY} by the year 2001 (Figure 7). Extended projection at the long term target (F=0.26) suggests that the stock will be maintained at levels above B_{MSY} and yield 95% of MSY. Stochastic projection of control rules based on longer rebuilding periods indicates that the proportion of simulated projections that achieve B_{MSY} in the desired time period substantially decreases. For example, only 40% of simulations of a rebuilding target F=0.16 (based on a five year rebuilding period) attained B_{MSY} by the year 2002.

Discussion

The rebuilding simulations and control rule described here can be applied to any stock with reliable estimates of *r* and *K*. Most production models require a

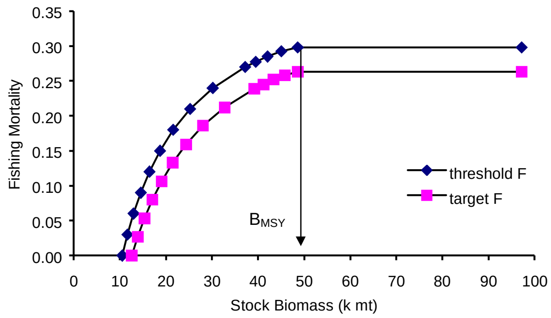

Figure 6. Proposed control rule for Georges Bank yellowtail flounder.

time series which encompasses a broad range of stock biomass and yield to provide dependable parameter estimates (Prager et al. 1996). In cases where the data series is not informative enough to reliably estimate all parameters, independent data can be used to fix certain parameters. For example, Prager (1993) fixed the value of *r* to provide guidance on MSY, but fixing *r* will determine the level of F_{MSY}. Application of ASPIC to other stocks in the northeast U.S. demonstrates that values of *q* can be fixed according to VPA estimates of stock biomass, or *B1R* values can be fixed according to ancillary information to provide reliable estimates of MSY conditions[2]. However, targets that are based on bootstrap distributions from such strongly constrained models may be risk prone, because the probability distributions are conditional on the accuracy and precision of the fixed parameter values.

The shape of the control rule will change according to the estimate of *r* (see Figure 3) or the specified rebuilding period (see Figure 5), and target F's will be closer to threshold F's as uncertainty decreases. Appropriate rebuilding periods may be determined from estimates of cumulative risk of not attaining B_{MSY} in the specified period. For the Georges Bank yellowtail flounder stock, the cumulative risk of not reaching B_{MSY} in four years using target F from the control rule is approximately 40% for the current stock conditions. Allowing a longer rebuilding period and a higher target F substantially increases the risk of not attaining B_{MSY} on schedule.

Alternatively, rebuilding times can be chosen based on the biomass at which rebuilding isopleths intersect the abcissa (F=0). For example, rebuilding periods may be based on maintaining a minimum biomass of $\frac{1}{4}B_{MSY}$, below which target F is zero[2]. In comparison to the control rule for Georges Bank yellowtail flounder, rebuilding periods must be longer than four years for slower-growing stocks (r<0.6) and shorter than four years for faster-growing stocks (r>0.6) in order to maintain $\frac{1}{4}B_{MSY}$. Advocating a target F of zero when stock biomass falls below $\frac{1}{4}B_{MSY}$ may appear overly restrictive, but similar management advice was offered for the example stock without an explicit control rule: In 1993, when stock biomass was approximately 10,000 mt, the 18th Northeast Regional Stock Assessment Review Committee concluded that the stock had 'collapsed' and recommended that, 'Fishing mortality on the Georges Bank yellowtail stock should be reduced to levels approaching zero' (NEFSC 1994).

The proposed targets incorporate a constant probability level of exceeding F thresholds (approximately 10%). However, a more conservative approach would entail lower risk at low stock sizes, and perhaps more risk at high stock sizes[2]. Many alternative control rules can be derived using the same rebuilding isopleths and bootstrap distributions reported here.

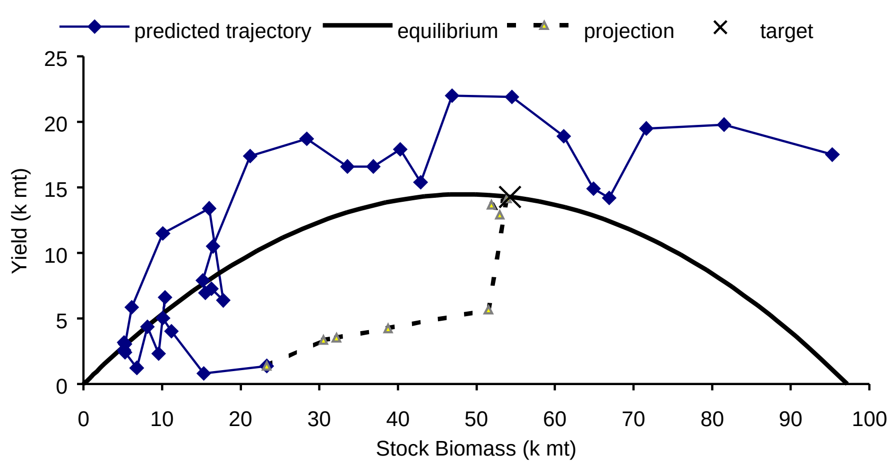

Figure 7. Projection of yield and biomass for Georges Bank yellowtail flounder with four years at the rebuilding target (F=0.11) and three years at the long-term target (F=0.26).

[2] Overfishing Definition Review Panel. 1998. Evaluation of existing overfishing definitions and recommendations for new overfishing definitions to comply with the Sustainable Fisheries Act. New England Fishery management Council Report.

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